

## **Geoacoustic Inversion and the Evaluation of Model and Parameter Uncertainties**

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Award Numbers: N00014-05-1-0264 and N00014-09-1-0313

<http://www.mpl.ucsd.edu>

### **LONG-TERM GOALS**

The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

### **OBJECTIVES**

The development of methods for estimating the entire posteriori probability densities of the geoacoustic parameters being investigated along with the mapping of these parameter uncertainties through to characterizations of applied interest (e.g. transmission loss), the development of new geoacoustic inversion procedures for use into the kHz frequency regime, the use of ambient noise for initial estimation of seafloor layering structure, and the demonstration of these methods in the analysis of data collected during the Shallow Water 2006 (SW06) experiment.

### **APPROACH**

Geoacoustic inversion involves a number of components: (a) representation of the ocean environment, (b) the inversion procedure selected (e.g. genetic algorithm or simulated annealing) including the forward propagation model implemented, and (c) the estimation of uncertainties associated with the parameter estimates. The latter is critical to facilitate the mapping of these uncertainties into characterizations of applied interest including the prediction of total system performance.

The reporting of geoacoustic parameter estimates without their associated uncertainties is of limited value. Of substantial greater utility is the complete *a posteriori* probability density (in general, the joint density between all parameters being estimated). One significant benefit of obtaining accurate *a posteriori* densities of the geoacoustic parameters is the potential to map these through to characterizations of applied interest (e.g. transmission loss, source detection and localization performance, etc.) in order to quantify those uncertainties as well.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>2010</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2010 to 00-00-2010</b>	
4. TITLE AND SUBTITLE <b>Geoacoustic Inversion and the Evaluation of Model and Parameter Uncertainties</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>University of California,Scripps Institution of Oceanography,Marine Physical Laboratory,La Jolla,CA,92093-0701</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>7</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

Substantial experience exists in the application of full-field geoacoustic inversion methods. These have been implemented in a number of geometries (e.g. fixed vertical and horizontal arrays, towed arrays, and sonobuoys) and have been shown to work well at low frequencies ( $< 1$  kHz). The application of these methods at higher frequencies (into the few kHz frequency regime) is at an early stage. New methods are required which are robust to modest geoacoustic heterogeneity (seafloor parameters as well as bathymetry) and temporal fluctuations (sound speed structure, surface waves, and array dynamics).

Ambient noise provides a natural illumination source that can be used for waveguide parameter estimation purposes. Our specific interest here is in the use of ambient noise to provide initial estimates of seafloor layering structure. Rough estimates of seafloor bathymetry and sediment thickness are needed to parameterize the waveguide model prior to carrying out a geoacoustic inversion procedure regardless of the type of data used for the inversion itself (e.g. source tow data, the radiated signature of ships of opportunity, or ambient noise).

The Shallow Water 2006 experiment took place in July-September 2006 on the outer edge of the New Jersey continental shelf in approximately 80 m deep water. Both narrowband and broadband transmissions (source tows and stations) were made over a wide range of frequencies (50 Hz – 5 kHz) including detailed measurements of seafloor structure and water column variability. These data are available for geoacoustic inversion purposes and the investigation of how nuisance parameter uncertainty (e.g. water column sound speed variability) couples into seafloor parameter uncertainty.

## **WORK COMPLETED**

The Shallow Water 2006 experiment took place in July-September 2006. One component of our analysis has focused on short range broadband geoacoustic inversion [1, 6, 7] when the source was approximately 200 m from the VLA. Due to the presence of complex microstructure in the thermocline of the oceanic sound-speed profile, fluctuations both in amplitude and arrival time of the direct path arrivals were observed. Time variation of the water-column environment was also evident during the source transmissions. To mitigate the effects of the ocean environment on the seabed property estimation, a multistage optimization inversion was employed.

One application of passive estimation of the time-domain Green's function is in the use of cross-correlations of upward and downward pointing VLA beams observing ambient noise to extract seabed layer structure (i.e. a passive fathometer) [2, 5]. The use of adaptive beamforming techniques is advantageous since at lower frequencies the horizontal component of the ambient noise field can be significant [2]. This so called passive fathometer technique exploits the naturally occurring acoustic sounds generated on the sea-surface, primarily from breaking waves. The method is based on the cross-correlation of noise from the ocean surface with its echo from the seabed, which recovers travel times to significant seabed reflectors. To limit averaging time and make this practical, beamforming is used with a vertical array of hydrophones to reduce interference from horizontally propagating noise. The initial development used conventional beamforming, but significant improvements have been realized using adaptive techniques. Adaptive methods for this process are described in [2] and applied to several data sets to demonstrate improvements possible as compared to conventional processing. An analytical model is presented in [5] for the passive fathometer response to ocean surface noise, interfering discrete noise sources, and locally uncorrelated noise in an ideal waveguide. The leading order term from the ocean surface noise produces the cross-correlation of vertical multipaths, yielding the depth of sub-bottom reflectors.

Finally, we have explored incorporating Kalman and particle filter tracking techniques into the geoacoustic inversion problem [3, 4]. This enables spatial and temporal tracking of environmental parameters and their underlying probability densities, making geoacoustic tracking a natural extension to geoacoustic inversion techniques.

## RESULTS

In many cases, it is of interest to estimate geoacoustic parameters over a larger spatial region rather than just the parameters characterizing propagation between a fixed source and receiver (or receiving array) location. Data might be available at a moored vertical receiving array from a towed acoustic sound source or a source might be received by a towed horizontal array. In both cases, the typical approach would be to treat each record of data independently of the others and carry out a full geoacoustic inversion for every record resulting in a sequence of geoacoustic parameter estimates and, in some cases, posteriori probability densities of the environmental parameters. The latter enables the environmental uncertainty to be projected into other waveguide characterizations such as propagation loss and its uncertainty.

Rather than treating the data records independently of one another, the geoacoustic inversion problem can be reformulated as tracking the evolution of these parameters and their associated uncertainties in space and time. This is achieved by merging geoacoustic inversion techniques with sequential filtering such as the Kalman and particle filters, see Figs. 1-2. The interaction between the environmental parameters and the acoustic field can involve a high level of nonlinearity. In addition, the posteriori probability densities of geoacoustic parameters can be non-Gaussian. Thus, geoacoustic tracking requires tracking filters that can handle nonlinear, non-Gaussian systems. We have demonstrated the suitability of three such filters in geoacoustic tracking— the extended Kalman filter (EKF), the unscented Kalman filter (UKF), and the particle filter (PF) on real data from the SWellEx-96 experiment [3].

In a review paper we have studied the basis and use of sequential filtering in ocean acoustics [4]. Sequential filtering provides an optimal framework for estimating and updating the unknown parameters of a system as data become available. Despite significant progress in the general theory and implementation, sequential Bayesian filters have been sparsely applied to ocean acoustics. The foundations of sequential Bayesian filtering with emphasis on practical issues are first presented covering both Kalman and particle filter approaches. Filtering becomes a powerful estimation tool, employing prediction from previous estimates and updates stemming from physical and statistical models that relate acoustic measurements to the unknown parameters. Ocean acoustic applications are then reviewed focusing on the estimation of environmental parameters evolving in time or space. Some possible scenarios for geoacoustic inversion are shown in Fig. 3.

We demonstrated the use of PF on event S9 from SWellEx-96 [3]. The environment is given in Fig. 4. Event S9 is selected here since the track is perpendicular to bathymetric lines giving the highest rate of change of the environment as the source ship moved into shallower water. Even though the source is successfully tracked by using a 200-particle PF, a second filtering is performed using a 10 000-particle PF. This enables us to obtain much better histograms of particles that represent the marginal posterior PDFs of the geoacoustic parameters. Evolving marginal posterior PDFs of the four geoacoustic parameters are given in Fig. 5. The water depth is well determined throughout the track and the posterior PDFs correspond to narrow Gaussian PDFs. The slope of the sediment sound speed profile is likewise well-determined, closely following the underlying true values obtained from a SWellEx

region database. Note, however, that both the sediment thickness and top layer sound speed have highly non-Gaussian, quickly-evolving posterior PDFs with multiple peaks.

## **IMPACT / APPLICATIONS**

Geoacoustic inversion techniques are of general interest for the estimation of waveguide parameters thus facilitating system performance prediction in shallow water. Natural transition paths for these results will be the PEO-C4I Battlespace Awareness and Information Operations Program Office (PMW-120) and the Naval Oceanographic Office.

## **RELATED PROJECTS**

This project is one of several sponsored by ONR Code 321OA to participate in the Shallow Water 2006 experiment and participate in the analysis of the resulting data.

## **PUBLICATIONS**

[1] Jiang, Yongmin, N. Ross Chapman, and Peter Gerstoft (2010), “Estimation of marine sediment properties using a hybrid differential evolution method,” IEEE J. Oceanic Engr. 35(1): 59-69, doi:10.1109/JOE.2009.2025904. [published, refereed]

[2] Siderius, Martin, Heechun Song, Peter Gerstoft, William S. Hodgkiss, Paul Hursky, Chris Harrison (2010), “Adaptive passive fathometer processing,” J. Acoust. Soc. Am. 127(4): 2193-2200, doi: 10.1121/1.3303985. [published, refereed]

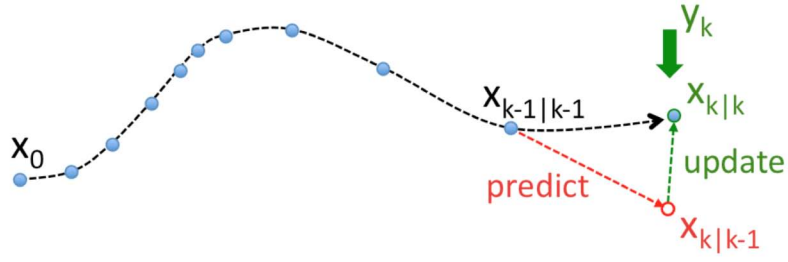
[3] Yardim, Caglar, Peter Gerstoft and W.S. Hodgkiss (2010), “Geoacoustic and source tracking using particle filtering: Experimental results,” J. Acoust. Soc. Am. 128(1): 75-87, doi:10.1121/1.3438475. [published, refereed]

[4] Yardim, Caglar, Zoi-Heleni Michalopoulou, and Peter Gerstoft (2010), “An overview of sequential Bayesian filtering in ocean acoustics,” IEEE J. Oceanic Engr. (submitted).

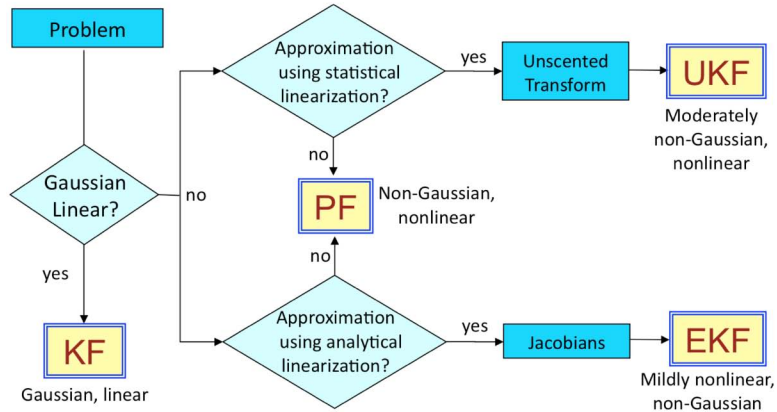
[5] Traer, James P. Gerstoft and W.S. Hodgkiss (2010), “Ocean bottom profiling with ambient noise: A model for the passive fathometer,” J. Acoust. Soc. Am. (submitted).

[6] Cheolsoo Park, Woojae Seong, Peter Gerstoft, and W.S. Hodgkiss (2010), “Fluctuating arrivals of short-range acoustic data,” J. Acoust. Soc. Am. (submitted).

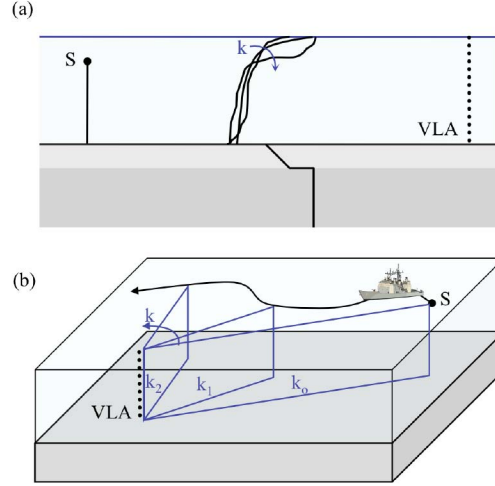
[7] Cheolsoo Park, Woojae Seong, Peter Gerstoft, and W.S. Hodgkiss (2010), “Geoacoustic inversion using back-propagation,” IEEE J. Oceanic Engr., doi:10.1109/JOE.2010.2040659. [in press, refereed]



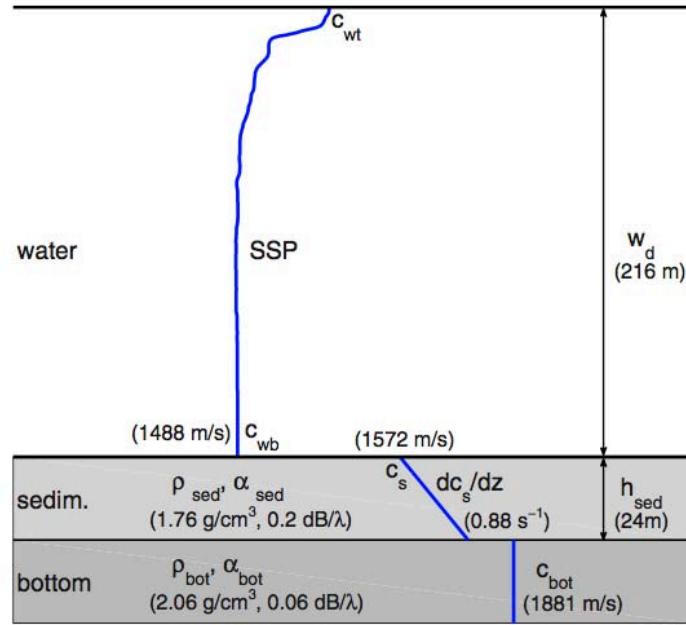
**Figure 1. Sequential Bayesian filtering.** From state  $x_{k-1}$ , state  $x_k$  is first predicted via the state equation, providing  $x_{k|k-1}$ . As data  $y_k$  becomes available, the observation equation is employed to update state  $x_{k|k-1}$ , providing  $x_{k|k}$ .



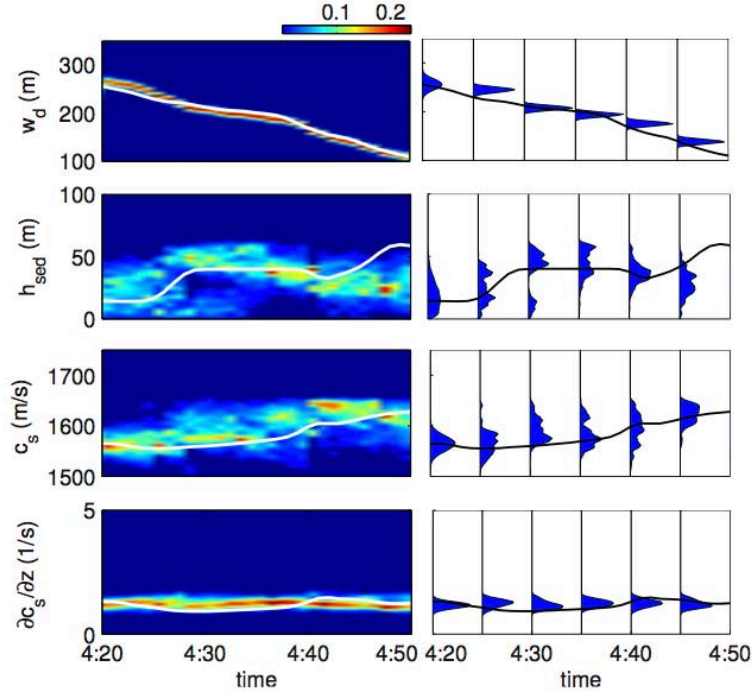
**Figure 2. A quick guide to filter selection leading to the Kalman filter (KF), extended Kalman filter (EKF), unscented Kalman filter (UKF), and particle filter (PF).**



**Figure 3. Geoacoustic environmental tracking: (a) Temporal tracking of the ocean sound speed profile for a fixed-receiver and a fixed-source and (b) tracking of the changing environment between the receiver and a moving source. Here shown for a vertical line array (VLA) of receivers.**



**Figure 4. The environmental parameters used to model the vertical profiles at the VLA and source for event S9 from SWellEx-96. The values in parentheses are at the location of the VLA.**



**Figure 5. Evolving marginal posterior PDFs for the geoaoustic parameters: (a) water depth ( $w_d$ ), (b) sediment thickness ( $h_{sed}$ ), (c) sediment sound speed at the water-sediment interface ( $c_s$ ), and (d) sediment sound speed gradient ( $\partial c_s / \partial z$ ). Vertical slices of the PDFs are given at 5 min intervals. Solid lines represent the true values.**